

# **$J/\psi$ polarization measurements in $p+p$ collisions at $\sqrt{s} = 200$ and 500 GeV with the STAR experiment**

**Barbara Trzeciak** <sup>\*†‡</sup>

*Faculty of Nuclear Sciences and Physical Engineering*

*Czech Technical University in Prague*

*Brehova 7, 115 19 Prague 1, Czech Republic*

*E-mail: [b.a.trzeciak \(at\) uu.nl](mailto:b.a.trzeciak@uu.nl)*

In these proceedings, measurements of  $J/\psi$  polarization in  $p + p$  collisions at  $\sqrt{s} = 200$  and 500 GeV via the dielectron decay channel at mid-rapidity with the STAR experiment are discussed. At  $\sqrt{s} = 200$  GeV the polarization parameter,  $\lambda_\theta$ , related to the polar anisotropy is obtained in the helicity frame as a function of transverse momentum,  $2 < p_T < 6$  GeV/c, and compared to different model predictions. A new  $J/\psi$  polarization measurement at  $\sqrt{s} = 500$  GeV extends the previous analysis to a wide transverse momentum range of  $5 < p_T < 16$  GeV/c. Also, the polarization parameter related to the azimuthal anisotropy,  $\lambda_\phi$ , is extracted in addition to  $\lambda_\theta$ , in two reference frames: the helicity and Collins-Soper frames. This allows for the frame invariant parameter calculation *vs*  $p_T$  in these two frames.

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<sup>\*</sup>For the STAR Collaboration

<sup>†</sup>Now at Faculty of Science, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands

<sup>‡</sup>Speaker.

## 1. Introduction

J/ψ is a bound state of charm (c) and anti-charm ( $\bar{c}$ ) quarks. Final charmonium states have to be colorless, however they can be formed via a color-singlet (CS) or color-octet (CO) intermediate  $c\bar{c}$  state. Based on this, there are different models that try to describe  $c\bar{c}$  pair production and hadronization to the physical charmonium state, such as Color Singlet Model (CSM), Color Evaporation Model (CEM), or more sophisticated Non-Relativistic QCD (NRQCD) calculations. CSM assumes that J/ψ is created through the color-singlet intermediate state only, with the same quantum numbers as the final charmonium state. In the NRQCD approach  $c\bar{c}$  color-octet intermediate states, in addition to the color-singlet states, can bind to form charmonia.

The charmonium production mechanism in elementary particle collisions is still not yet exactly known. For many years measurements of the J/ψ cross section have been used to test different J/ψ production models. While many models can describe relatively well the experimental data on the J/ψ cross section in p + p collisions [1, 2, 3, 4, 5, 6, 7, 8], they have different predictions for the J/ψ polarization. Therefore, measurements of the J/ψ polarization may allow to discriminate among different models and provide new insight into the J/ψ production mechanism.

## 2. J/ψ polarization measurements with the STAR experiment

In STAR, the J/ψ polarization has been analyzed at mid-rapidity at  $\sqrt{s} = 200$  and 500 GeV using the J/ψ di-electron decay channel. The STAR detector [9] is a multi-purpose detector that has a large acceptance at mid-rapidity,  $|\eta| < 1$ , with a full azimuthal coverage. The Time Projection Chamber (TPC) [10] is the main tracking system and is used to identify particles via the ionization energy loss ( $dE/dx$ ) measurement. Identification of high- $p_T$  J/ψ is possible using the Barrel Electromagnetic Calorimeter (BEMC) [11] which allows to trigger on high- $p_T$  electrons and that improves high- $p_T$  electron identification. Furthermore, the Time Of Flight (TOF) detector [12] enhances the electron identification capability at low momenta where the  $dE/dx$  bands for electrons and hadrons overlap.

### 2.1 Method

J/ψ polarization is measured via the angular distribution of the electrons from J/ψ decay:

$$\frac{d^2N}{d(\cos\theta)d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi \quad (2.1)$$

where  $\theta$  and  $\phi$  are polar and azimuthal angles, respectively;  $\lambda_\theta$ ,  $\lambda_\phi$  and  $\lambda_{\theta\phi}$  are the angular decay coefficients. The polar angle  $\theta$  is defined as an angle between the positron momentum vector in the J/ψ rest frame and a chosen polarization axis. When integrated over  $\phi$  or  $\cos\theta$ , the decay angular distribution has following forms:

$$W(\cos\theta) \propto 1 + \lambda_\theta \cos^2\theta \quad (2.2)$$

$$W(\phi) \propto 1 + \frac{2\lambda_\phi}{3 + \lambda_\theta} \cos 2\phi \quad (2.3)$$

respectively.

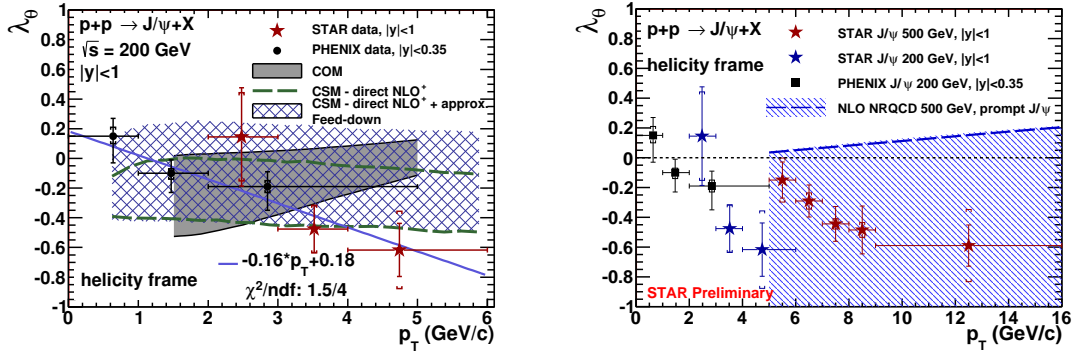
In STAR inclusive J/ψ polarization has been measured in two reference frames: the helicity (HX) and Collins-Soper (CS) frames. In the HX frame the polarization axis is defined along the J/ψ momentum in the center-of-mass frame of colliding beams, and in the CS frame the polarization axis is a bisector of the angle formed by one beam direction and the opposite direction of the other beam, in the J/ψ rest frame. Furthermore, since values of measured polarization parameters depend on a chosen polarization axis, a frame invariant parameter has been proposed [13]:

$$\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi} \quad (2.4)$$

Value of the parameter is independent of the chosen reference frame and so is a very good cross-check of measurements performed in different frames.

### 3. J/ψ polarization results

STAR has performed the first J/ψ polarization measurement at  $\sqrt{s} = 200$  GeV at mid-rapidity and  $2 < p_T < 6$  GeV/c, in the HX frame [14]. The left panel of Fig. 1 shows the  $p_T$  dependence of  $\lambda_\theta$ . The STAR result is shown together with the PHENIX measurement at the same energy and in a lower  $p_T$  range [15]. The results are also compared to LO NRQCD calculations (COM) [16] and the NLO<sup>+</sup> CSM predictions [17]. The trend observed in the RHIC data is towards longitudinal polarization as  $p_T$  increases and, within experimental and theoretical uncertainties, the result is consistent with the NLO<sup>+</sup> CSM prediction.

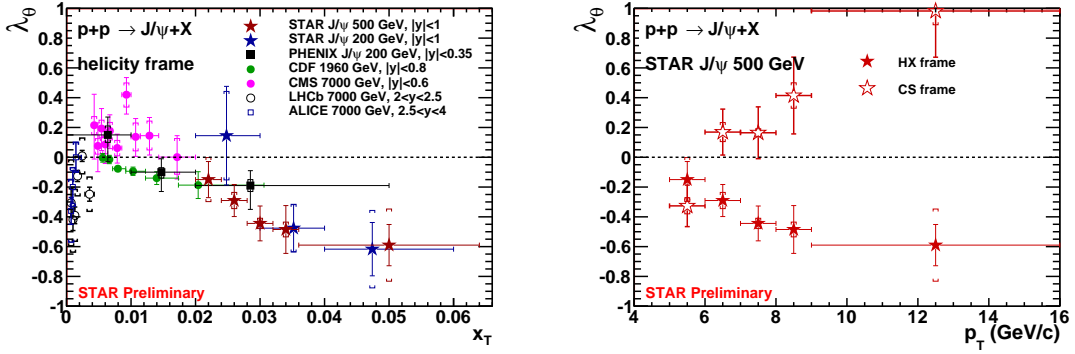


**Figure 1:** Left: J/ψ polarization parameter  $\lambda_\theta$  vs  $p_T$  at  $|y| < 1$  [14] compared to the PHENIX measurement [15] and two model predictions [16, 17]. Right: J/ψ polarization parameter  $\lambda_\theta$  vs  $p_T$  at  $\sqrt{s} = 500$  GeV at mid-rapidity compared to results at  $\sqrt{s} = 200$  GeV and to the NLO NRQCD calculations [18, 19, 20, 21]

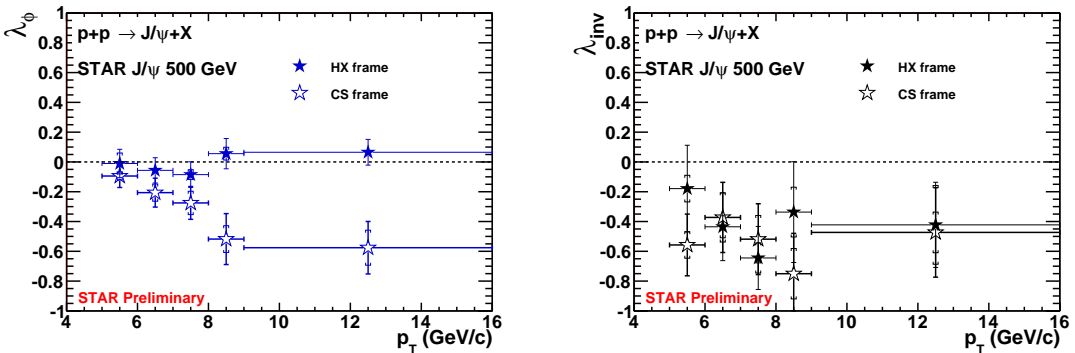
Due to limited statistics of the dataset at  $\sqrt{s} = 200$  GeV, only the  $\lambda_\theta$  parameter related to the polar anisotropy has been extracted. The J/ψ polarization measurements have been extended to a wider  $p_T$  range of 5-16 GeV/c using p+p dataset at  $\sqrt{s} = 500$  GeV.  $\cos\theta$  and  $\phi$  distributions integrated over  $\phi$  and  $\cos\theta$ , respectively, are fitted simultaneously with Eq. 2.2, 2.3 in order to obtain  $\lambda_\theta$  and  $\lambda_\phi$  coefficients in each analyzed  $p_T$  bin. The same trend of  $\lambda_\theta$  towards strong negative values is observed at  $\sqrt{s} = 500$  GeV as at  $\sqrt{s} = 200$  GeV in the HX frame. The results are shown in the right panel of Fig. 1 and are also compared to a NLO NRQCD prediction [18, 19,

20, 21] at  $\sqrt{s} = 500$  GeV for the prompt J/ψ production. The lower limit for  $\lambda_\theta$  is unconstrained within the NRQCD calculations and the new data points should help to constrain color-octet Long-Distance Matrix Elements for the model. Since similar trend of  $\lambda_\theta$  as a function of  $p_T$  is observed at RHIC for both analyzed colliding energies and two analyzed  $p_T$  ranges, a comparison of the parameter values at different colliding energies as a function of  $x_T = 2p_T/\sqrt{s}$  has been performed. The left panel of Fig. 2 shows  $\lambda_\theta$  vs  $x_T$  from RHIC, Tevatron and LHC experiments, and a common trend of  $\lambda_\theta$  decreasing with increasing  $x_T$  is observed.

Also, there is no strong azimuthal anisotropy observed in the HX frame at  $\sqrt{s} = 500$  GeV. Measured values of the  $\lambda_\phi$  parameter are consistent with zero, as is shown in the left panel of Fig. 3. To cross-check the measurement, both  $\lambda_\theta$  and  $\lambda_\phi$  parameters have been extracted in the CS frame in addition to the HX frame. The  $\lambda_\theta$  is shown in the right panel of Fig. 2 and the  $\lambda_\phi$  is depicted in the left panel of Fig. 3. Results in the CS frame are shown as open symbols and compared to the results in the HX frame presented as solid points. We observe different  $p_T$  dependence of the parameters. However, the frame invariant parameters,  $\lambda_{inv}$ , are in agreement between the frames and  $\lambda_{inv}$  has negative values in both frames, as shown in the right panel of Fig. 3.



**Figure 2:** Left:  $\lambda_\theta$  vs  $x_T = 2p_T/\sqrt{s}$  in the HX frame. Right:  $\lambda_\theta$  vs  $p_T$  in the HX (closed symbols) and CS frame (open symbols).



**Figure 3:** Left:  $\lambda_\phi$  vs  $p_T$  in the HX (closed symbols) and CS frame (open symbols). Right:  $\lambda_{inv}$  vs  $p_T$  in the HX (closed symbols) and CS frame (open symbols).

#### 4. Summary

STAR has measured J/ψ polarization at  $\sqrt{s} = 200$  and 500 GeV at mid-rapidity. At both energies a trend of  $\lambda_\theta$  parameter towards negative values with increasing  $p_T$  is observed in the helicity frame. The result at  $\sqrt{s} = 200$  GeV is consistent with the NLO<sup>+</sup> CSM prediction. Also, a common  $x_T$  dependence of RHIC, Tevatron and LHC  $\lambda_\theta$  measurements is observed. At  $\sqrt{s} = 500$  GeV there is no azimuthal anisotropy seen in the helicity frame:  $\lambda_\phi$  values are consistent with zero. The 500 GeV result has been also cross-checked by performing polarization analysis in the Collins-Soper frame. Different trends of  $\lambda_\theta$  and  $\lambda_\phi$  parameter values are observed but the frame invariant parameters  $\lambda_{inv}$  are in agreement between the frames.

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